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ASTM B 117 Screening of Nonchromate Conversion Coatings on Aluminum Alloys 2024, 2219, 5083, and 7075 Using DOD Paint Systems

by Brian E. Placzankis, Chris E. Miller,
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1. Introduction

Eight candidate hexavalent chromium (Cr^{+6}) free conversion coatings for evaluation on aluminum alloys were selected based upon feedback from U.S. Navy, U.S. Air Force (USAF), U.S. Army, and National Aeronautics and Space Administration (NASA) representatives at an initial meeting with personnel representing the Environmental Security Technology Certification Program (ESTCP) and the Joint Group on Pollution Prevention (JG-PP). Most funding for this study was provided by these organizations. The overall nonchromate study consists of two phases: phase I laboratory validation of alternatives through extensive coupon tests to evaluate paint adhesion, corrosion resistance and other criteria, and phase II field testing and process validation of selected alternatives at various user facilities.

As in a previous study [1] of these Cr^{+6} alternatives, the focus of this particular report is constrained to phase I laboratory data. This report specifically examines American Society for Testing and Materials (ASTM) B 117 [2] accelerated corrosion exposure of aluminum Al 2024, 2219, 5083, and 7075 specimens treated with the candidate hexavalent chromium-free pretreatments as well as one hexavalent chromium-based pretreatment (Alodine 1200S) used as a control. In order to closely match conditions found in currently fielded equipment, five organic coating systems commonly used in fielded Department of Defense (DOD) systems were selected.

2. Experimental Procedure

Al panels (each nominally 7.62 × 12.7 cm) of alloys 2024-T3, 2219-T87, 5083-H131, and 7075-T6 were obtained. Prior to pretreatment and testing, all coupons were clearly labeled using a mechanical scribe to permanently affix the experimental designation. Twenty-five panels with each pretreatment combination were prepared for each alloy for neutral salt fog exposure. Each set of 25 panels was further subdivided into 5 groups, one for each of the five selected DOD coatings. The five DOD coating systems applied were:

- MIL-PRF-23377 [3] high solid epoxy primer with MIL-PRF-85285 [4] high solid polyurethane topcoat (USAF/U.S. Navy).
- MIL-PRF-85582c1 [5] waterborne epoxy primer with MIL-PRF-85285 topcoat (U.S. Navy).
- MIL-PRF-85582nc waterborne epoxy chromium-free formulation primer with MIL-PRF-85285 topcoat (Experimental/JG-PP/USAF/Navy/Boeing).

- MIL-P-53030 [6] water-reducible epoxy primer with MIL-C-53039 [7] chemical agent resistant single component polyurethane topcoat (U.S. Army/U.S. Marine Corps [USMC]).
- MIL-P-53022 [8] epoxy primer with MIL-C-53039 polyurethane topcoat (U.S. Army/USMC).

The first two coating systems, 23377/85285 and 85582c1/85285, each contained hexavalent chromium compounds in their primer formulations; therefore, elimination of Alodine 1200S pretreatment would only reduce the total hexavalent chromium present in these cases. The remaining three coating systems (85582nc/85285, 53030/53039, and 53022/53039) were chromium free. The two U.S. Army/USMC coating systems meet chemical agent resistant coating (CARC) specifications.

Prior to painting, all of the panels were cleaned and pretreatments were applied per each of the pretreatment manufacturers specifications at the U.S. Naval Air Systems Command (NAVAIR) facilities. The coating system's respective primer coats were applied within 24 hr after the pretreatment application to each group of five panels for each pretreatment for each alloy. The topcoats were applied after 24 hr primer cure. The full coating system was then cured at ambient conditions for 14 days. The panels were then delivered from NAVAIR to the U.S. Army Research Laboratory (ARL) test facilities. Figure 1 depicts a schematic detailing the ASTM B 117 neutral salt fog panel test matrix.

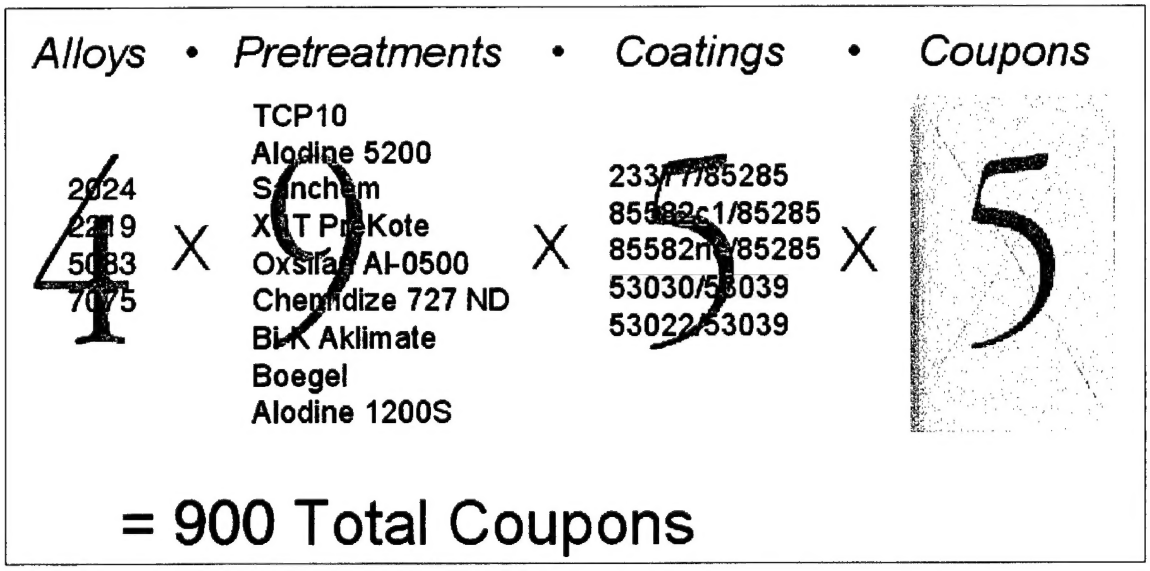


Figure 1. ASTM B 117 test panel matrix breakdown.

One large corrosion test chamber was used to evaluate all of the coated aluminum test panels (Figure 2). Immediately prior to exposure, the panels were all "X" scribed using a standard carbide-tipped hardened steel scribe. The scribed panels were placed into the chamber and

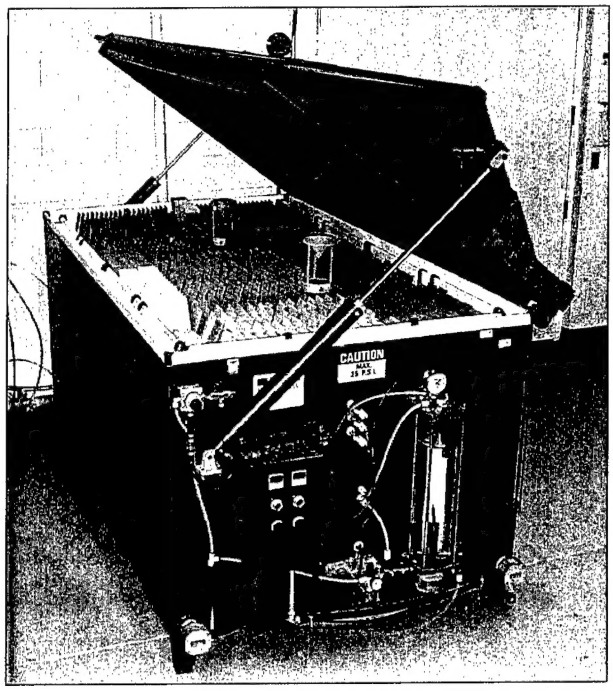


Figure 2. Test chamber and panels used for ASTM B 117.

exposed to ASTM B 117 neutral salt fog conditions consisting of 95 °F with saturated humidity and atomized fog of 5% NaCl solution. In order to chronicle the corrosion, specimens were numerically rated for damage at weekly intervals up to 3 weeks followed by subsequent inspections at 500-hr intervals up to 3000 hr or until specimen group failure using method ASTM D 1654 [9]. Specimen group failures were defined when three or more of the panels in a particular alloy/pretreatment/coating set were measured with a rating of "0" under method ASTM D 1654. In addition, the representative panels rated from each of the five test panels were digitally scanned at 600-dpi resolution and saved as high-quality graphics files. In order to facilitate easier viewing of the inevitable large quantities of data from this matrix, color codes were assigned based upon ranges of ASTM D 1654 ratings. Table 1 depicts the ASTM D 1654 rating parameters and also defines the colors and their respective rating ranges.

3. Results

With the exception of the early failures previously defined under ASTM D 1654, the coated panels were all subjected to 3000 hr of ASTM B 117. The creepback ratings at the designated intervals for the representative panels are characterized in Tables 2–21. In addition, final 3000-hr creepback ratings for all panels are listed and characterized in the Appendix. The prevalent failure mode for most of the panels was blistering along the scribe. In addition to the creepback severity color coding assigned in Table 1, additional corrosion characterization

Table 1. Evaluation of painted of coated specimens subjected to corrosive environments–ASTM D 1654.

Rating of Failure at Scribe (Procedure A)		
Representative Mean Creepage From Scribe		Rating
(mm)	(in)	Number
		10
		9
		8
Over 1.0 to 2.0	1/32 to 1/16	7
Over 2.0 to 3.0	1/16 to 1/8	6
Over 3.0 to 5.0	1/8 to 3/16	5
Over 5.0 to 7.0	3/16 to 1/4	4

Note: Solid colors depict normal scribe creepback from corrosion.

Table 2. ASTM D 1654 scribe creepback ratings for Al 2024 coated with 23377/85285.

Panel #	Pretreatment	1 Week	2 Weeks	3 Weeks	1000 hr	1500 hr	2000 hr	2500 hr	3000 hr
2-001	Alodine 1200S								
2-101	TCP10								
2-201	Alodine 5200								
2-302	Sanchem 7000				6				
2-401	X-IT PreKote								
2-501	Oxsilan AI-0500								
2-601	Chemidize 727ND								
2-701	Bi-K Aklimate								
2-801A	Boegel								

Note: Solid colors depict normal scribe creepback from corrosion.

through application of textures to the color coded cells is provided in the tables. Figure 3 details these additional characterizations and provides examples. In cases where blistering occurred away from the scribe, the table cells appear with diagonal crosshatching. In situations where coating creepback from the scribe resulted from adhesion loss, vertical crosshatching was used. In a few rare situations, mixed failure mode consisting of nonscribe blistering with adhesion loss at the scribe occurred. In these situations a finer textured crosshatching pattern was used.

Table 3. ASTM D 1654 scribe creepback ratings for Al 2024 coated with 85582c1/85285.

Panel #	Pretreatment	1 Week	2 Weeks	3 Weeks	1000 hr	1500 hr	2000 hr	2500 hr	3000 hr
2-056	Alodine 1200S								
2-106	TCP10								
2-206	Alodine 5200								
2-307	Sanchem 7000			9	7	7	7	7	7
2-407	X-IT PreKote								
2-508	Oxsilan AI-0500								
2-606	Chemidze 727ND								
2-706	Bi-K Aklimate							8	8
2-806A	Boegel								

Notes: Solid colors depict normal scribe creepback from corrosion.
Vertical crosshatching denotes adhesion failure.
Diagonal crosshatching denotes blistering away from immediate scribe regions.

Table 4. ASTM D 1654 scribe creepback ratings for Al 2024 coated with 85582nc/85285.

Panel #	Pretreatment	1 Week	2 Weeks	3 Weeks	1000 hr	1500 hr	2000 hr	2500 hr	3000 hr
2-011	Alodine 1200S						7	7	7
2-111	TCP10				6	5	5	5	4
2-211	Alodine 5200				6	5	5	5	5
2-311	Sanchem 7000	9	8	8	8	8	8	8	8
2-411	X-IT PreKote				8	8	8	8	8
2-511	Oxsilan AI-0500					7	7	7	7
2-611	Chemidze 727ND				8	7	8	8	8
2-711	Bi-K Aklimate		6	6	6	6	6	6	6
2-811A	Boegel				7	6	6	5	5

Notes: Solid colors depict normal scribe creepback from corrosion.
Vertical crosshatching denotes adhesion failure.
Diagonal crosshatching denotes blistering away from immediate scribe regions.

Table 5. ASTM D 1654 scribe creepback ratings for Al 2024 coated with 53030/53039.

Panel #	Pretreatment	1 Week	2 Weeks	3 Weeks	1000 hr	1500 hr	2000 hr	2500 hr	3000 hr
2-016	Alodine 1200S								7
2-116	TCP10	9	7	6	6	6	6	6	6
2-216	Alodine 5200								7
2-316	Sanchem 7000	7	7	7	7	7	7	7	7
2-416	X-IT PreKote		7	7	7	7	7	7	7
2-519	Oxsilan AI-0500	8	8	8	8	8	8	8	8
2-616	Chemidze 727ND								
2-716	Bi-K Aklimate								
2-817A	Boegel				7	6	6	5	5

Notes: Solid colors depict normal scribe creepback from corrosion.
Vertical crosshatching denotes adhesion failure.

Table 6. ASTM D 1654 scribe creepback ratings for Al 2024 coated with 53022/53039.

Panel #	Pretreatment	1 Week	2 Weeks	3 Weeks	1000 hr	1500 hr	2000 hr	2500 hr	3000 hr
2-025	Alodine 1200S		6						
2-121	TCP10			7	6				
2-221	Alodine 5200				7	6			
2-324	Sanchem 7000								
2-425	X-IT PreKote								
2-523	Oxsilan Al-0500								
2-622	Chemidze 727ND								
2-721	Bi-K Aklimate								
2-821A	Boegel					7	7	7	

Note: Solid colors depict normal scribe creepback from corrosion.

Table 7. ASTM D 1654 scribe creepback ratings for Al 2219 coated with 23377/85285.

Panel #	Pretreatment	1 Week	2 Weeks	3 Weeks	1000 hr	1500 hr	2000 hr	2500 hr	3000 hr
9-001	Alodine 1200S								
9-101	TCP10								
9-201	Alodine 5200								
9-301	Sanchem 7000	7							
9-401	X-IT PreKote	9	9	9	9	9	9	9	7
9-501	Oxsilan Al-0500							7	7
9-602	Chemidze 727ND	7	7	6					
9-701	Bi-K Aklimate	9	9	9	9	9	9	7	6
9-801A	Boegel			7					

Notes: Solid colors depict normal scribe creepback from corrosion.
Vertical crosshatching denotes adhesion failure.

Table 8. ASTM D 1654 scribe creepback ratings for Al 2219 coated with 85582c1/85285.

Panel #	Pretreatment	1 Week	2 Weeks	3 Weeks	1000 hr	1500 hr	2000 hr	2500 hr	3000 hr
9-006	Alodine 1200S								
9-106	TCP10								
9-206	Alodine 5200								
9-306	Sanchem 7000	6	6	6	5	5	5	5	5
9-406	X-IT PreKote	9	9	9	9	9	9	9	9
9-506	Oxsilan Al-0500				8	8	8	8	8
9-606	Chemidze 727ND	9	9	7	7	7	7	7	7
9-706	Bi-K Aklimate	9	9	9	9	9	9	6	6
9-806A	Boegel	7	7	7	7	7	6	6	6

Notes: Solid colors depict normal scribe creepback from corrosion.
Vertical crosshatching denotes adhesion failure.
Fine textured crosshatching denotes adhesion failure AND blistering away from scribe.
Diagonal crosshatching denotes blistering away from immediate scribe regions.

Table 9. ASTM D 1654 scribe creepback ratings for Al 2219 coated with 85582nc/85285.

Panel #	Pretreatment	1 Week	2 Weeks	3 Weeks	1000 hr	1500 hr	2000 hr	2500 hr	3000 hr
9-011	Alodine 1200S							7	7
9-114	TCP10	7	7	7	7	6	6	6	6
9-213	Alodine 5200					7	7	6	6
9-314	Sanchem 7000	6	6	4					
9-411	X-IT PreKote		6	5	4				
9-511	Oxsilan Al-0500				7	7	7	6	6
9-611	Chemidze 727ND	7	7	7	5	5	4	4	4
9-713	Bi-K Aklimate	6	6						
9-811A	Boegel	7	7	7	5	5	5	4	4

Notes: Solid colors depict normal scribe creepback from corrosion.
Diagonal crosshatching denotes blistering away from immediate scribe regions.

Table 10. ASTM D 1654 scribe creepback ratings for Al 2219 coated with 53030/53039.

Panel #	Pretreatment	1 Week	2 Weeks	3 Weeks	1000 hr	1500 hr	2000 hr	2500 hr	3000 hr
9-017	Alodine 1200S				7	6	6	5	5
9-116	TCP10	7	7	7	6	5	5	5	5
9-219	Alodine 5200		7	6	5	5	5	4	4
9-318	Sanchem 7000	4							
9-416	X-IT PreKote	7	6	5					
9-520	Oxsilan Al-0500	5	4						
9-617	Chemidze 727ND	4							
9-716	Bi-K Aklimate								
9-816A	Boegel	6	5	4	4				

Note: Solid colors depict normal scribe creepback from corrosion.

Table 11. ASTM D 1654 scribe creepback ratings for Al 2219 coated with 53022/53039.

Panel #	Pretreatment	1 Week	2 Weeks	3 Weeks	1000 hr	1500 hr	2000 hr	2500 hr	3000 hr
9-021	Alodine 1200S	6							
9-121	TCP10	7	6	6	6	6	6	5	5
9-221	Alodine 5200	7	6	6	6	6			
9-323	Sanchem 7000								
9-421	X-IT PreKote								
9-523	Oxsilan Al-0500								
9-621	Chemidze 727ND			3	3	3	1	1	1
9-721	Bi-K Aklimate								
9-821A	Boegel	7	7	5	5	5	5		

Notes: Solid colors depict normal scribe creepback from corrosion.
Diagonal crosshatching denotes blistering away from immediate scribe regions.

Table 12. ASTM D 1654 scribe creepback ratings for Al 5083 coated with 23377/85285.

Panel #	Pretreatment	1 Week	2 Weeks	3 Weeks	1000 hr	1500 hr	2000 hr	2500 hr	3000 hr
5-001	Alodine 1200S								
5-101	TCP10								
5-201	Alodine 5200								
5-301	Sanchem 7000								
5-401	X-IT PreKote	9	9	9	9	9	9	9	9
5-501	Oxsilan Al-0500								
5-601	Chemidze 727ND								
5-701	Bi-K Aklimate								
5-801A	Boegel								

Notes: Solid colors depict normal scribe creepback from corrosion.
Vertical crosshatching denotes adhesion failure.

Table 13. ASTM D 1654 scribe creepback ratings for Al 5083 coated with 85582c1/85285.

Panel #	Pretreatment	1 Week	2 Weeks	3 Weeks	1000 hr	1500 hr	2000 hr	2500 hr	3000 hr
5-006	Alodine 1200S								
5-106	TCP10								
5-206	Alodine 5200								
5-306	Sanchem 7000				9	9	9	9	9
5-406	X-IT PreKote	9	9	9	9	9	9	9	9
5-506	Oxsilan Al-0500							7	7
5-606	Chemidze 727ND					9	9	9	9
5-706	Bi-K Aklimate						9	9	9
5-806A	Boegel								

Notes: Solid colors depict normal scribe creepback from corrosion.
Diagonal crosshatching denotes blistering away from immediate scribe region.
Vertical crosshatching denotes adhesion failure.

Table 14. ASTM D 1654 scribe creepback ratings for Al 5083 coated with 85582nc/85285.

Panel #	Pretreatment	1 Week	2 Weeks	3 Weeks	1000 hr	1500 hr	2000 hr	2500 hr	3000 hr
5-011	Alodine 1200S								
5-111	TCP10								
5-211	Alodine 5200								
5-311	Sanchem 7000	7							
5-411	X-IT PreKote	7							
5-511	Oxsilan Al-0500							7	7
5-611	Chemidze 727ND	7	6						
5-711	Bi-K Aklimate	7							
5-811A	Boegel		9	9	9	9	9	9	9

Notes: Solid colors depict normal scribe creepback from corrosion.
Vertical crosshatching denotes adhesion failure.

Table 15. ASTM D 1654 scribe creepback ratings for Al 5083 coated with 53030/53039.

Panel #	Pretreatment	1 Week	2 Weeks	3 Weeks	1000 hr	1500 hr	2000 hr	2500 hr	3000 hr
5-016	Alodine 1200S								
5-116	TCP10						7	7	6
5-216	Alodine 5200		7	7	6	6	6	6	6
5-316	Sanchem 7000	7	7						
5-416	X-IT PreKote			7					
5-516	Oxsilan Al-0500								
5-616	Chemidze 727ND								
5-718	Bi-K Aklimate								
5-816A	Boegel								

Note: Solid colors depict normal scribe creepback from corrosion.

Table 16. ASTM D 1654 scribe creepback ratings for Al 5083 coated with 3022/53039.

Panel #	Pretreatment	1 Week	2 Weeks	3 Weeks	1000 hr	1500 hr	2000 hr	2500 hr	3000 hr
5-021	Alodine 1200S								
5-121	TCP10								
5-221	Alodine 5200								
5-321	Sanchem 7000								
5-421	X-IT PreKote								
5-521	Oxsilan Al-0500								
5-621	Chemidze 727ND								
5-722	Bi-K Aklimate								
5-821A	Boegel		7	7					

Note: Solid colors depict normal scribe creepback from corrosion.

Table 17. ASTM D 1654 scribe creepback ratings for Al 7075 coated with 23377/85285.

Panel #	Pretreatment	1 Week	2 Weeks	3 Weeks	1000 hr	1500 hr	2000 hr	2500 hr	3000 hr
7-001	Alodine 1200S								
7-101	TCP10	0	0	0	0	0	0	0	0
7-201	Alodine 5200								
7-301	Sanchem 7000								
7-402	X-IT PreKote								
7-501	Oxsilan Al-0500								
7-601	Chemidze 727ND								
7-701	Bi-K Aklimate								
7-801A	Boegel								

Notes: Solid colors depict normal scribe creepback from corrosion.
Vertical crosshatching denotes adhesion failure.

Table 18. ASTM D 1654 scribe creepback ratings for Al 7075 coated with 85582c1/85285.

Panel #	Pretreatment	1 Week	2 Weeks	3 Weeks	1000 hr	1500 hr	2000 hr	2500 hr	3000 hr
7-006	Alodine 1200S								
7-106	TCP10	9	9	9	9	9	9	9	9
7-206	Alodine 5200								
7-306	Sanchem 7000	7	3	2	2	2	2	2	3
7-408	X-IT PreKote								
7-506	Oxsilan AI-0500								
7-606	Chemidze 727ND	9	6	5	5	5	5	5	5
7-706	Bi-K Aklimate		7	7	7	7	7	7	7
7-806A	Boegel								

Notes: Solid colors depict normal scribe creepback from corrosion.
Vertical crosshatching denotes adhesion failure.
Fine textured crosshatching denotes adhesion failure AND blistering away from scribe.

Table 19. ASTM D 1654 scribe creepback ratings for Al 7075 coated with 85582nc/85285.

Panel #	Pretreatment	1 Week	2 Weeks	3 Weeks	1000 hr	1500 hr	2000 hr	2500 hr	3000 hr
7-011	Alodine 1200S								
7-114	TCP10								
7-211	Alodine 5200								
7-311	Sanchem 7000		7	7	7	6			
7-413	X-IT PreKote	7	6						
7-511	Oxsilan AI-0500								
7-611	Chemidze 727ND								
7-711	Bi-K Aklimate		7						
7-811A	Boegel								

Notes: Solid colors depict normal scribe creepback from corrosion.
Vertical crosshatching denotes adhesion failure.

Table 20. ASTM D 1654 scribe creepback ratings for Al 7075 coated with 53030/53039.

Panel #	Pretreatment	1 Week	2 Weeks	3 Weeks	1000 hr	1500 hr	2000 hr	2500 hr	3000 hr
7-016	Alodine 1200S							7	7
7-116	TCP10							7	7
7-219	Alodine 5200	7	7	7	7	7	7	7	7
7-317	Sanchem 7000								
7-417	X-IT PreKote								
7-516	Oxsilan AI-0500								
7-616	Chemidze 727ND								
7-720	Bi-K Aklimate								
7-816A	Boegel		7	6					

Note: Solid colors depict normal scribe creepback from corrosion.

Table 21. ASTM D 1654 scribe creepback ratings for Al 7075 coated with 53022/53039.

Panel #	Pretreatment	1 Week	2 Weeks	3 Weeks	1000 hr	1500 hr	2000 hr	2500 hr	3000 hr
7-021	Alodine 1200S								7
7-121	TCP10								
7-222	Alodine 5200							7	6
7-322	Sanchem 7000		7	7	7	7	7	6	6
7-423	X-IT PreKote								
7-521	Oxsilan Al-0500								
7-624	Chemidize 727ND								
7-724	Bi-K Aklimate								
7-821A	Boegel		7	6	6	4	4	4	4

Note: Solid colors depict normal scribe creepback from corrosion.

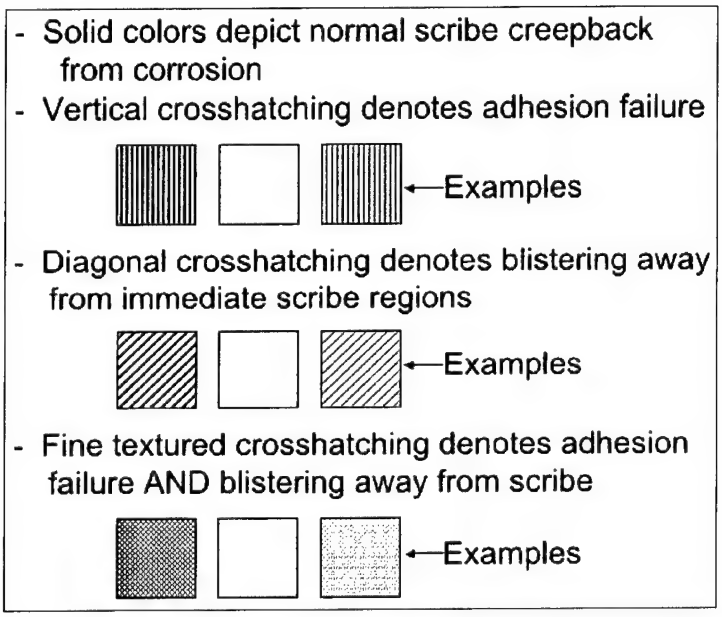


Figure 3. Color code shading patterned for detailed descriptions.

3.1 Al 2024

For Al 2024, the top performing pretreatments were clearly visible. For this particular alloy, it was the Cr^{+6} free coating systems that most aided in revealing the better performers. With the exception of the Sanchem process, all of the pretreatments for the hexavalent chromium bearing 23377/85285 coating system performed well and completed 3000 hr with the highest ratings among the coating systems (Table 2).

The 85582c1/85285 coating system also contains hexavalent chromium; overall it performed similar when compared vs. the 23377/85285 system for the same pretreatments. As with 23377/85285, Sanchem showed degradation, though not as severe. In addition to problems on Sanchem-treated panels, the Bi-K pretreatment had blistering *away* from the scribed areas past 2500 hr (Table 3).

The remaining three Cr^{+6} free coating systems: 85582nc/85285, 53030/53039, and 53022/53039 provided a much greater challenge for the pretreatments. At the conclusion of 3000 hr, all of the pretreatments including hexavalent Alodine 1200S showed significant corrosion damage. Many of the pretreatments were unable to sustain acceptable performance levels and were terminated prior to the end of 3000 hr. The most consistent performance among the three chromate-free coating systems was provided by the Boegel, Alodine 5200, NAVAIR TCP, and Alodine 1200S pretreatments (Tables 4–6, Figure 4). In the specific case of the 53022/53039 CARC system, Boegel and Alodine 5200 pretreatments even *exceeded* the performance for Alodine 1200S (Figure 5). The Brent Oxsilan pretreatment rendered respectable performance at or near the leaders for the 85582nc/85285 system but performed poorly on the U.S. Army's 53030/53039 and 53022/53039 CARC-based coating systems.

3.2 Al 2219

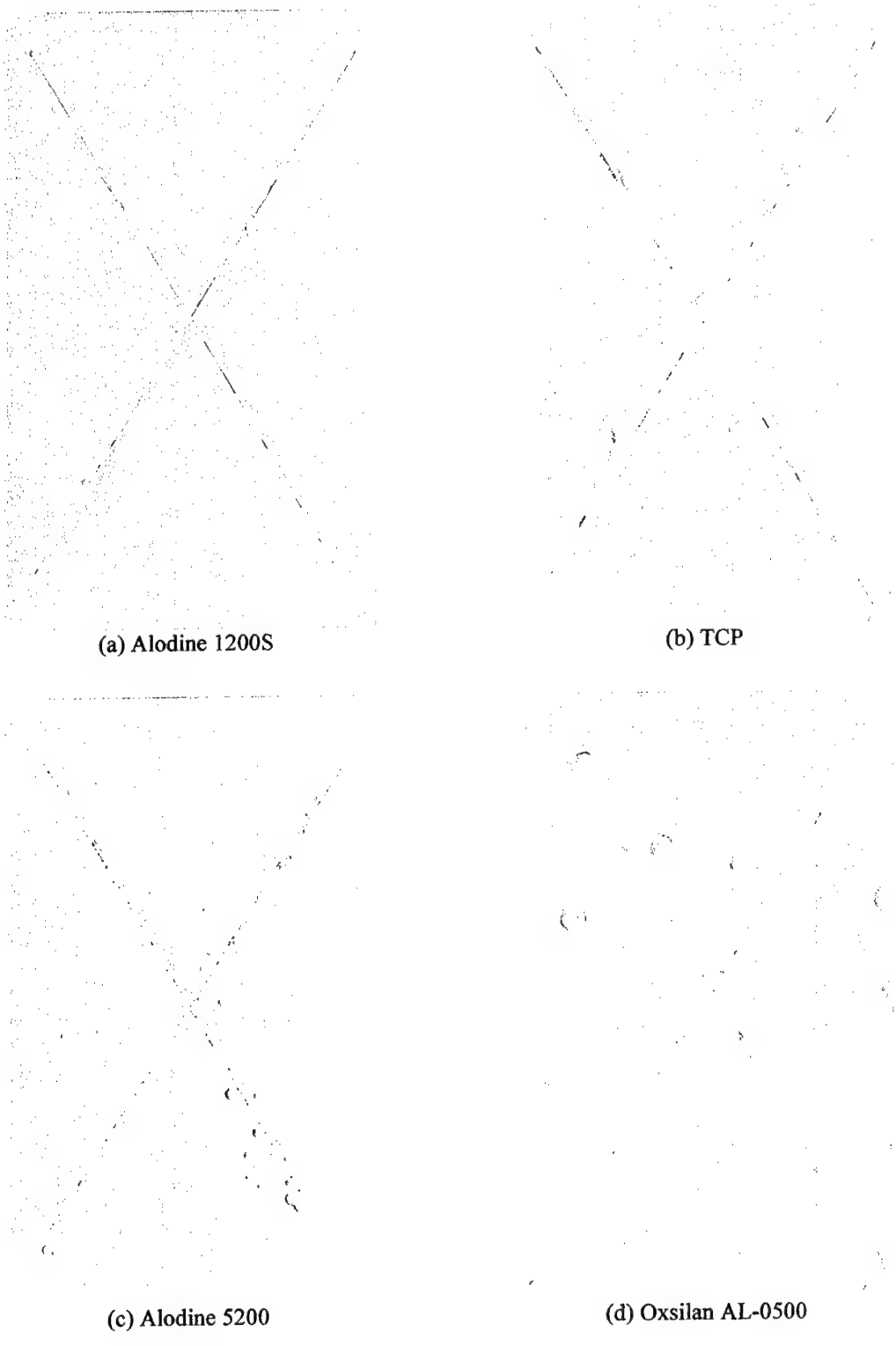
Of all of the Al alloys examined in this study, Al 2219 with its high copper (Cu) content is by far the most corrosion prone and provides a difficult situation for even hexavalent-based Alodine 1200S. For the chromate-based 23377/85285 coating system (although all pretreatments lasted the full 3000-hr duration) significant corrosion damage occurred on most of the pretreatments.

The best performers for this coating system were Alodines 1200S and 5200, the Brent Oxsilan pretreatment, and Bi-K. It should be noted that NAVAIR TCP had mixed results; two panel replicates rated "4" and "5" with the remaining three panels all rated at "9." For the chromate containing 85582c1/85285 system, the best performers were Alodines 1200S and 5200, NAVAIR TCP, X-IT PreKote, and Brent Oxsilan. The remaining pretreatments performed in the intermediate range with ratings ranging from 4 to 7.

For the three chromate-free coating systems: 85582nc/85285, 53030/53039, and 53022/53039, there was significant corrosion damage with many of the pretreatments unable to endure 3000 hr without failure. The most consistent performers for these systems were NAVAIR TCP, and Alodines 1200S and 5200. The Brent Oxsilan and Boegel pretreatments produced somewhat modest ratings vs. the leaders for the 85582nc/85285 coating system but performed much more poorly on the CARC-based systems (Tables 7–11, Figures 6 and 7).

3.3 Al 5083

Al 5083, well known for its stable protective oxide layer, does not usually significantly corrode, even under uncoated accelerated conditions. Due to its widespread use in ground systems, accelerated corrosion methods such as ASTM B 117 are still necessary for this alloy to detect potential adhesion and quality control issues. In contrast to a previous cyclic accelerated corrosion exposure studies under General Motors (GM) 9540P [1, 10, 11], surprisingly significant amounts of creepback corrosion via blistering were measured on the chromate-free coating systems. As with other alloys, the 23377/85285 coating system proved superior, and there was no significant creepback resulting from corrosion or coating system delamination (Table 12). For 85582c1/85285, blistering away



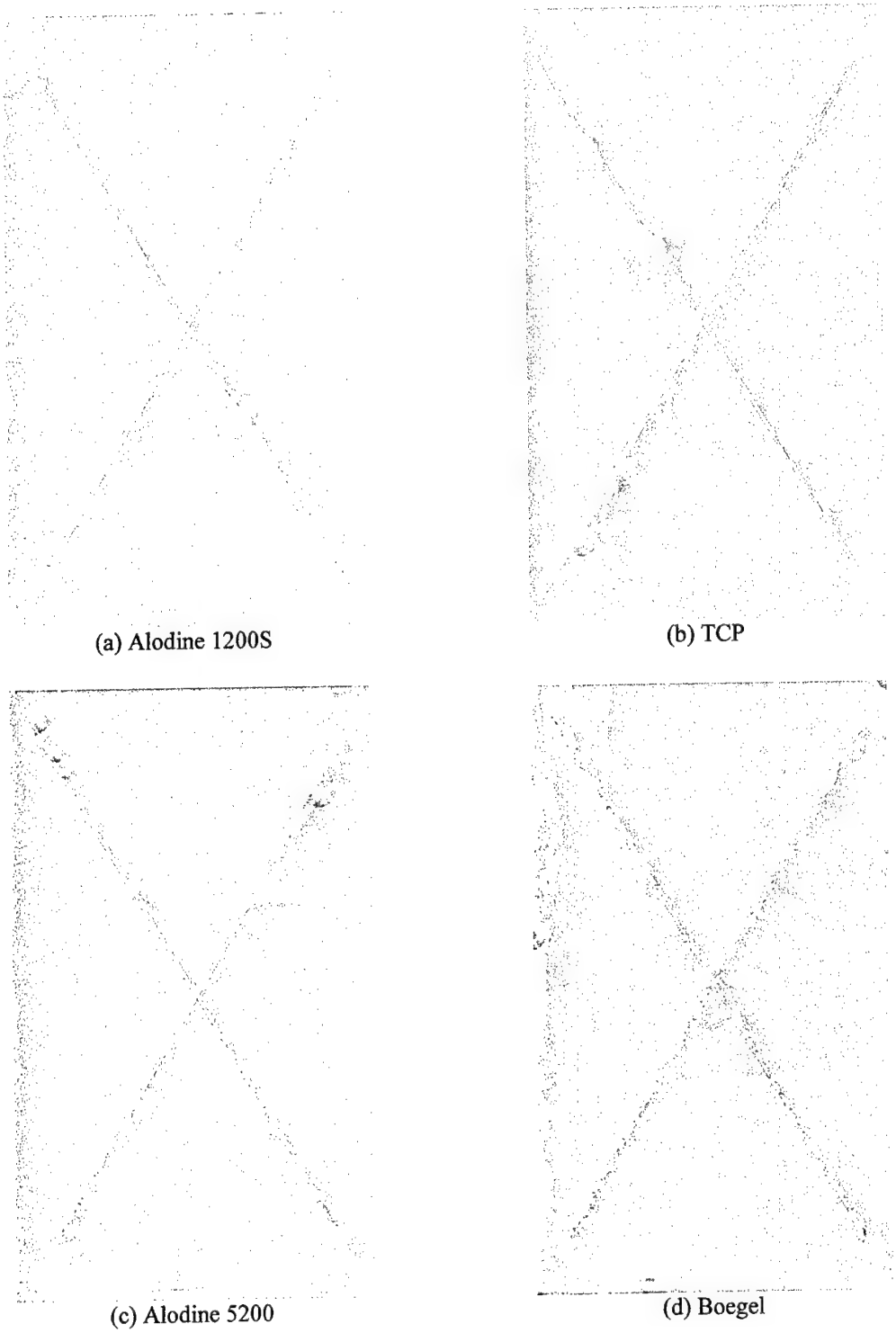
(a) Alodine 1200S

(b) TCP

(c) Alodine 5200

(d) Oxsilan AL-0500

Figure 4. Al 2024 with 85582nc/85285 at 3000-hr ASTM B 117.



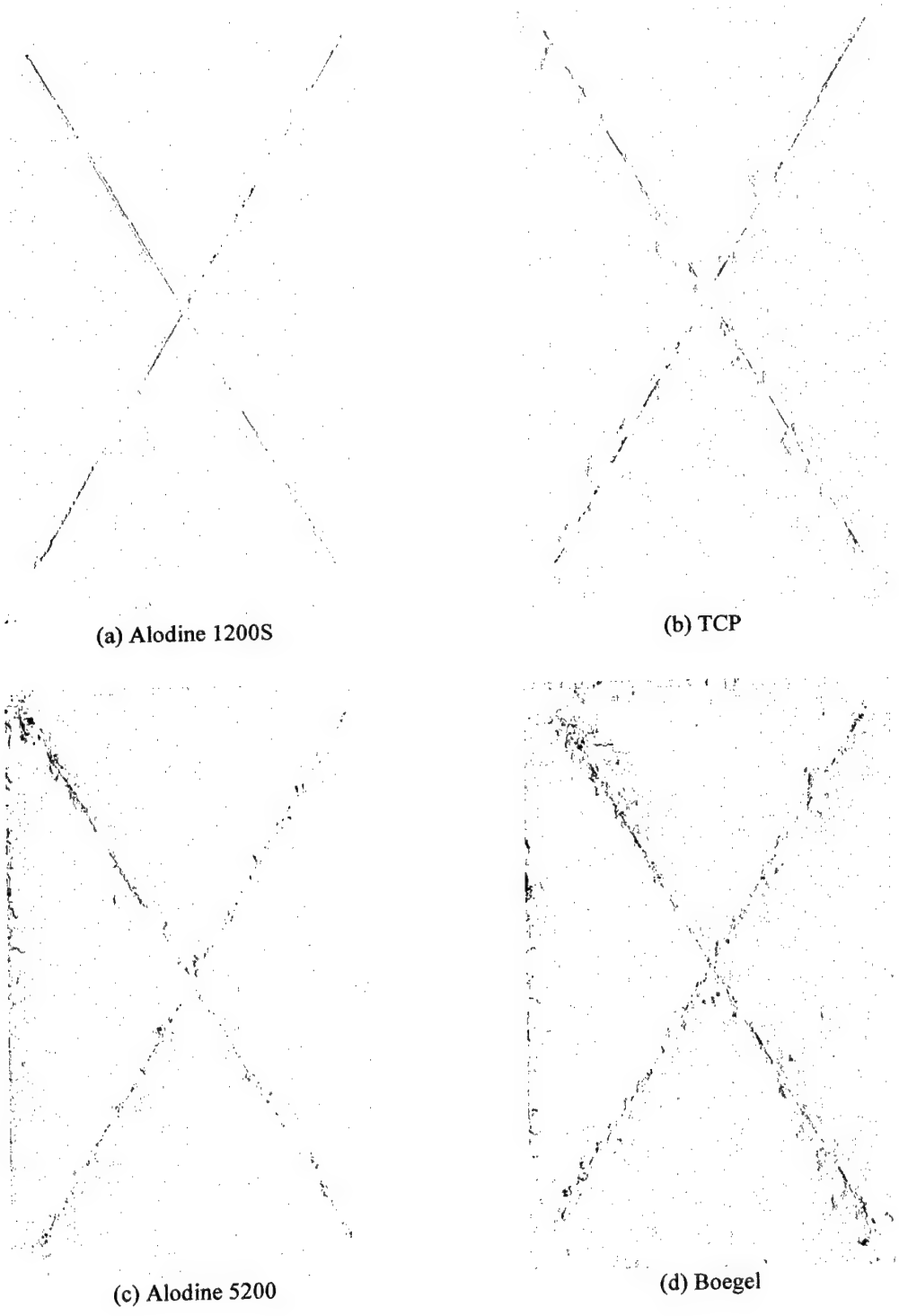
(a) Alodine 1200S

(b) TCP

(c) Alodine 5200

(d) Boegel

Figure 5. Al 2024 with 53030/53022 at 3000-hr ASTM B 117.



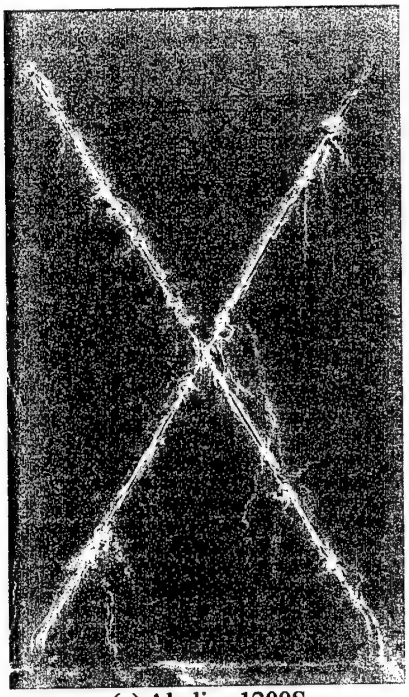
(a) Alodine 1200S

(b) TCP

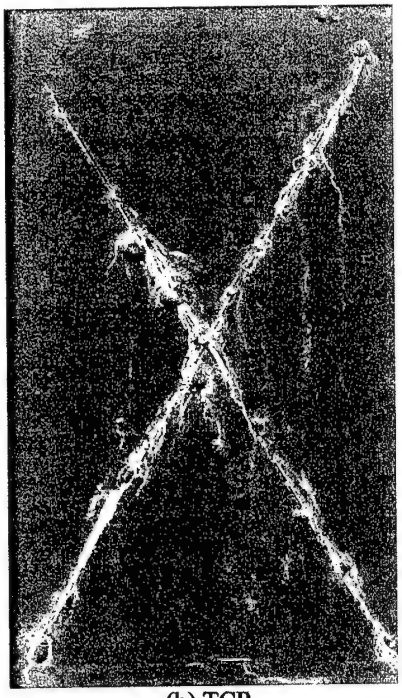
(c) Alodine 5200

(d) Boegel

Figure 6. Al 2219 with 85582nc/85285 at 3000-hr ASTM B 117.



(a) Alodine 1200S



(b) TCP

(c) Alodine 5200

(d) Boegel

Figure 7. Al 2219 with 53030/53039 at 3000-hr ASTM B 117.

from the scribe appeared at 1000 hr for Sanchem 7000. The Chemidize and Bi-K pretreatments also showed blistering away from the scribe appearing at 1500 and 2000 hr, respectively. Corrosion was most severe for the Brent Oxsilan pretreatment which rated a "7" beginning at 2500 hr. Although Table 13 shows almost all pretreatments rating "8" or "9" at 3000 hr, the best performers were NAVAIR TCP, Alodines 1200S and 5200, and Boegel, which achieved these ratings free of any other defects such as coating delamination.

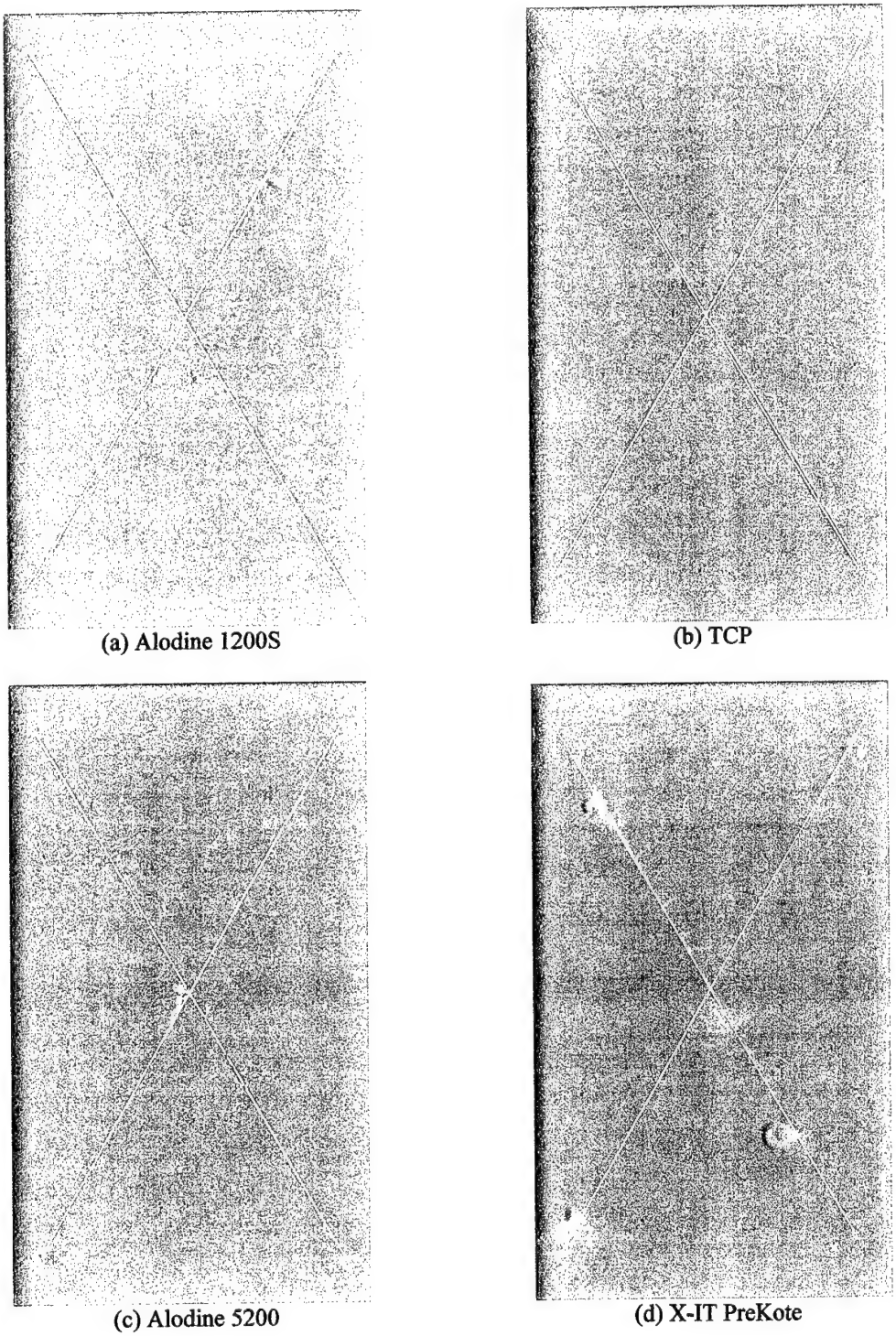
For the nonchromate-based formulations, the extent of corrosion measured on some of the pretreatments was surprisingly high for Al 5083 (Tables 14–16, Figures 8 and 9). However, this unexpected corrosion was useful in differentiating the effectiveness of the various pretreatments. For the 85582nc/85285 and 53022/53039 systems, the superiority of Alodines 1200S and 5200 and NAVAIR TCP pretreatments was obvious. For the 53030/53039 system, the ratings were significantly lower; however, Alodines 1200S and 5200 and NAVAIR TCP still performed better than the other pretreatments.

3.4 Al 7075

For the coating system 23377/85285 as in the other alloys, most all of the pretreatments performed well with little or no damage to the scribed region. All of the pretreatments rated "9" at the conclusion of 3000 hr (Table 17). One item of note was a slight lifting or delamination along the length of the entire scribe of the NAVAIR TCP. This delamination, first measured at week 1, was very slight and never progressed or ever degraded the rating below a "9."

For the 85582c1/85285 system, the top performers with little or no damage were Alodines 1200S and 5200, TCP, X-IT PreKote, and Boegel (Table 18). As with the 23377/85285 system, NAVAIR TCP displayed the same minor delamination issue. The other pretreatments for this system were disqualified either by lower ratings due to corrosion, delamination, or both. Brent Oxsilan Al-0500 pretreatment catastrophically failed prior to 2 weeks across the majority of its five panels. The massive delamination of this particular pretreatment was unique across the entire test matrix (Figures 10 and 11).

For the chromate-free systems, the most consistent performers were Alodines 1200S and 5200, and NAVAIR TCP (Tables 20 and 21). Unlike the chromate-containing coating systems, NAVAIR TCP pretreatment showed none of the minor coating delamination issues (Figures 12 and 13). Two notable but inconsistent performers were Oxsilan Al-0500 and Boegel, which performed extremely well on 85582nc/85285 yet performed poorly on the CARC systems.



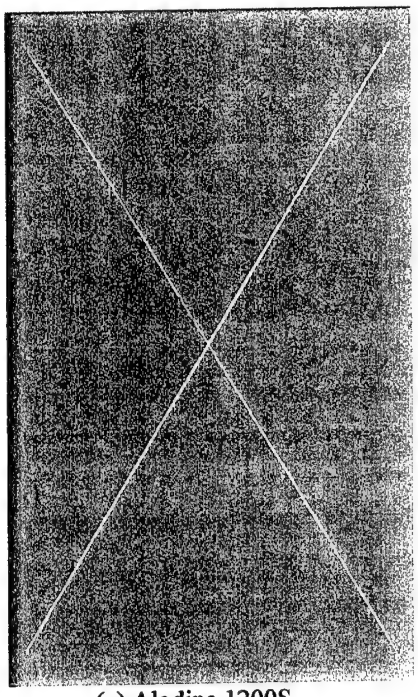
(a) Alodine 1200S

(b) TCP

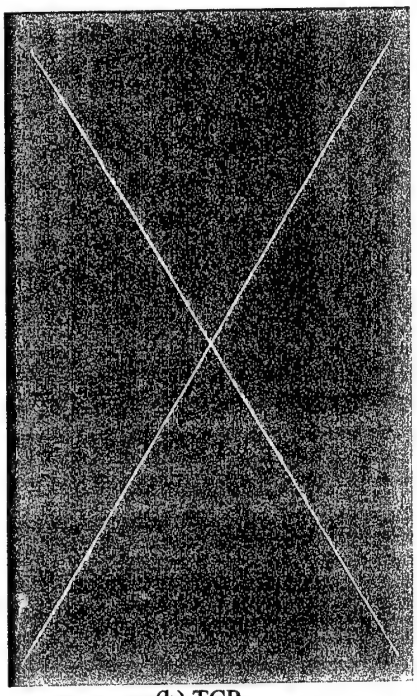
(c) Alodine 5200

(d) X-IT PreKote

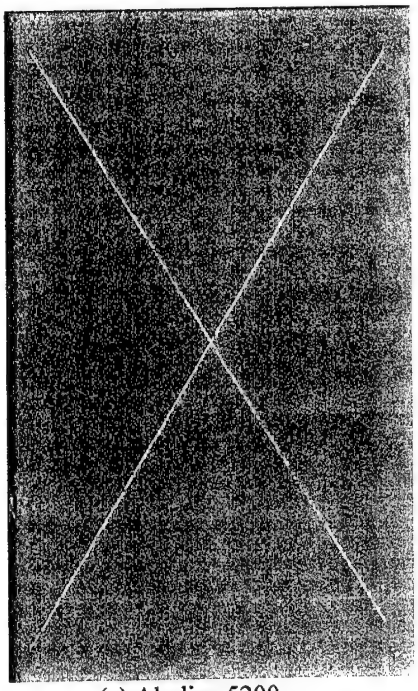
Figure 8. Al 5083 with 53030/53039 at 3000-hr ASTM B 117.



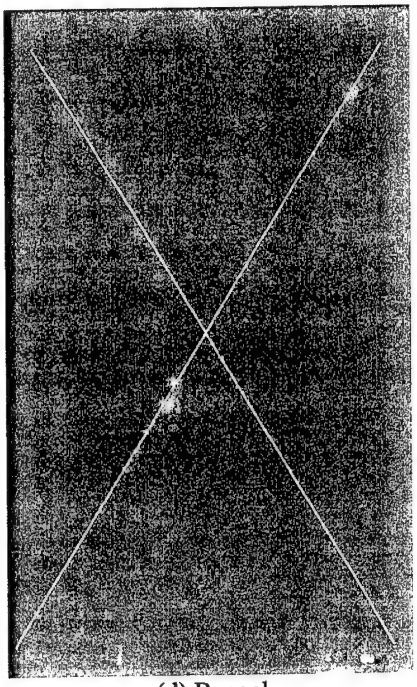
(a) Alodine 1200S



(b) TCP



(c) Alodine 5200



(d) Boegel

Figure 9. Al 5083 with 53022/53039 at 3000-hr ASTM B 117.

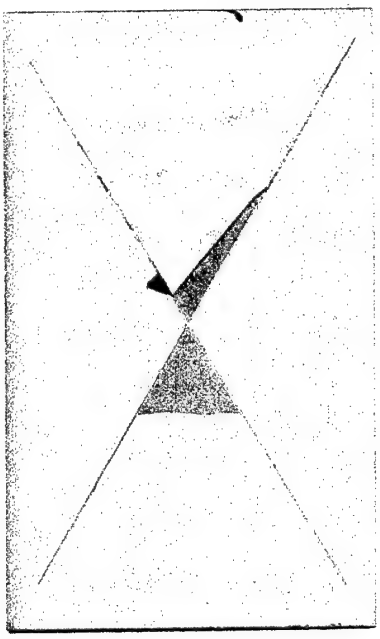


Figure 10. Severe delamination of Brent Oxsilan Al-0500 pretreated Al 7075 with 85582c1/85285 at 1 week ASTM B 117 exposure.

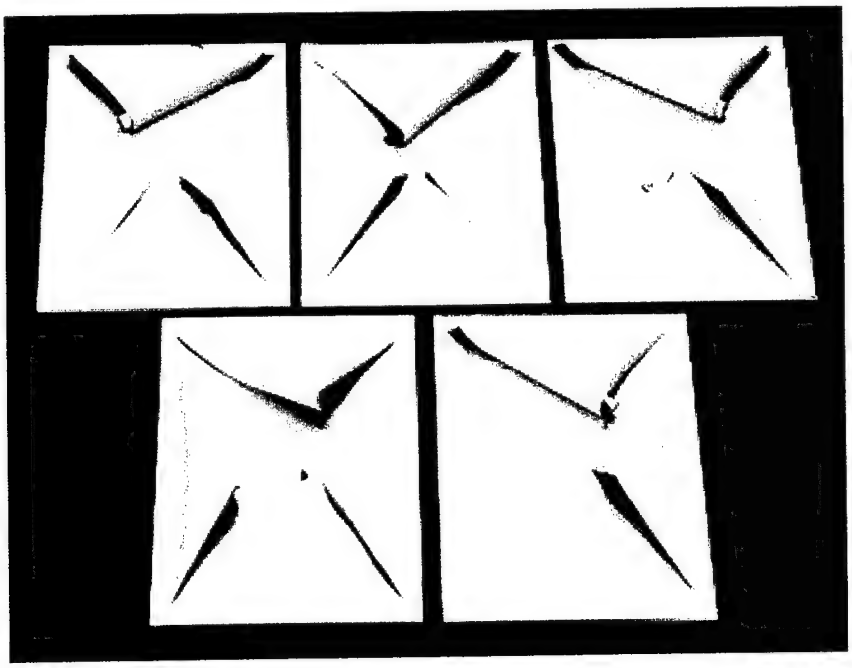


Figure 11. Severe delamination of Brent Oxsilan Al-0500 pretreated Al 7075 panels with 85582c1/85285 at 2 weeks ASTM B 117 exposure.

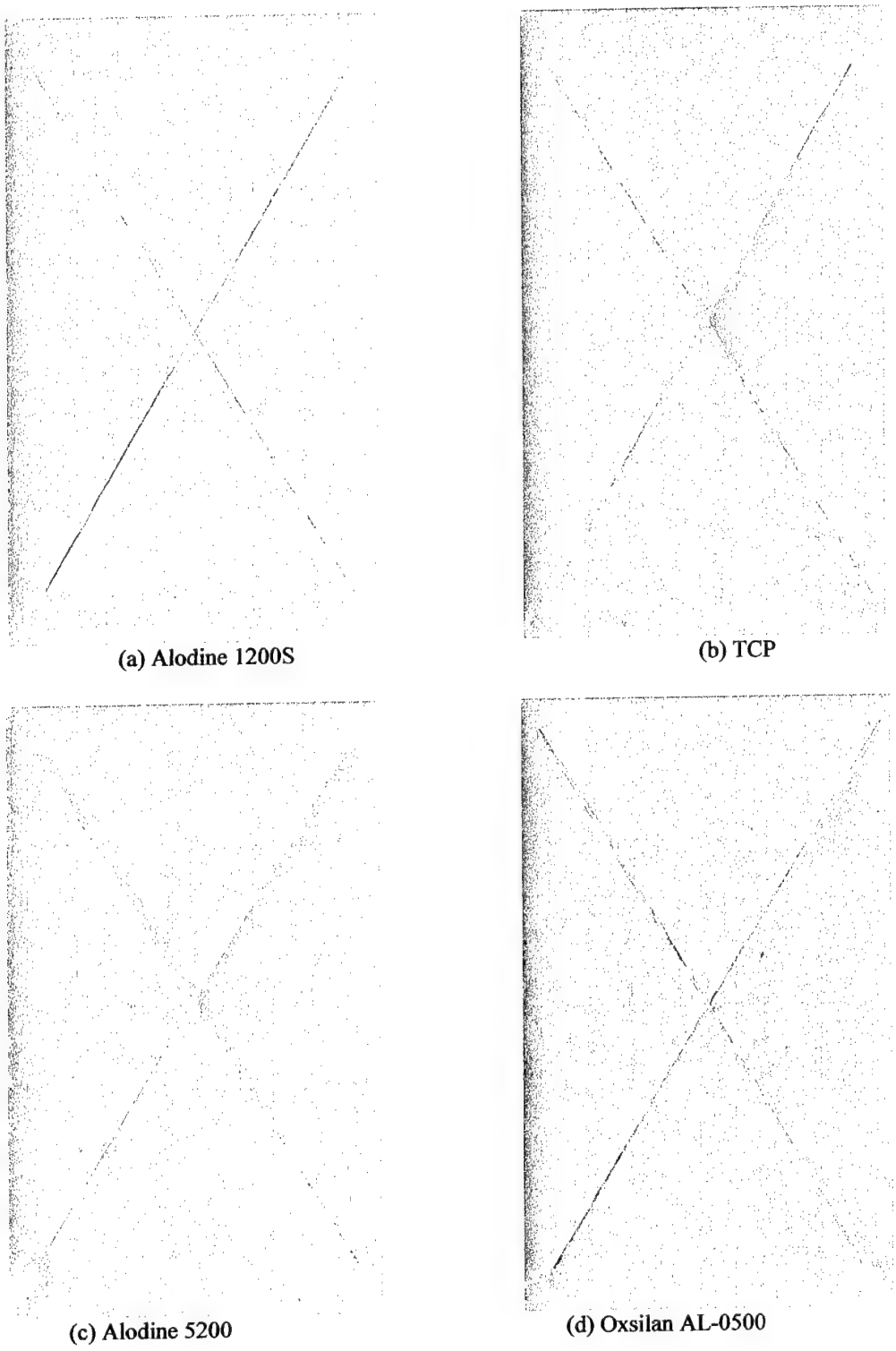


Figure 12. Al 7075 with 85582nc/85285 at 3000-hr ASTM B 117.

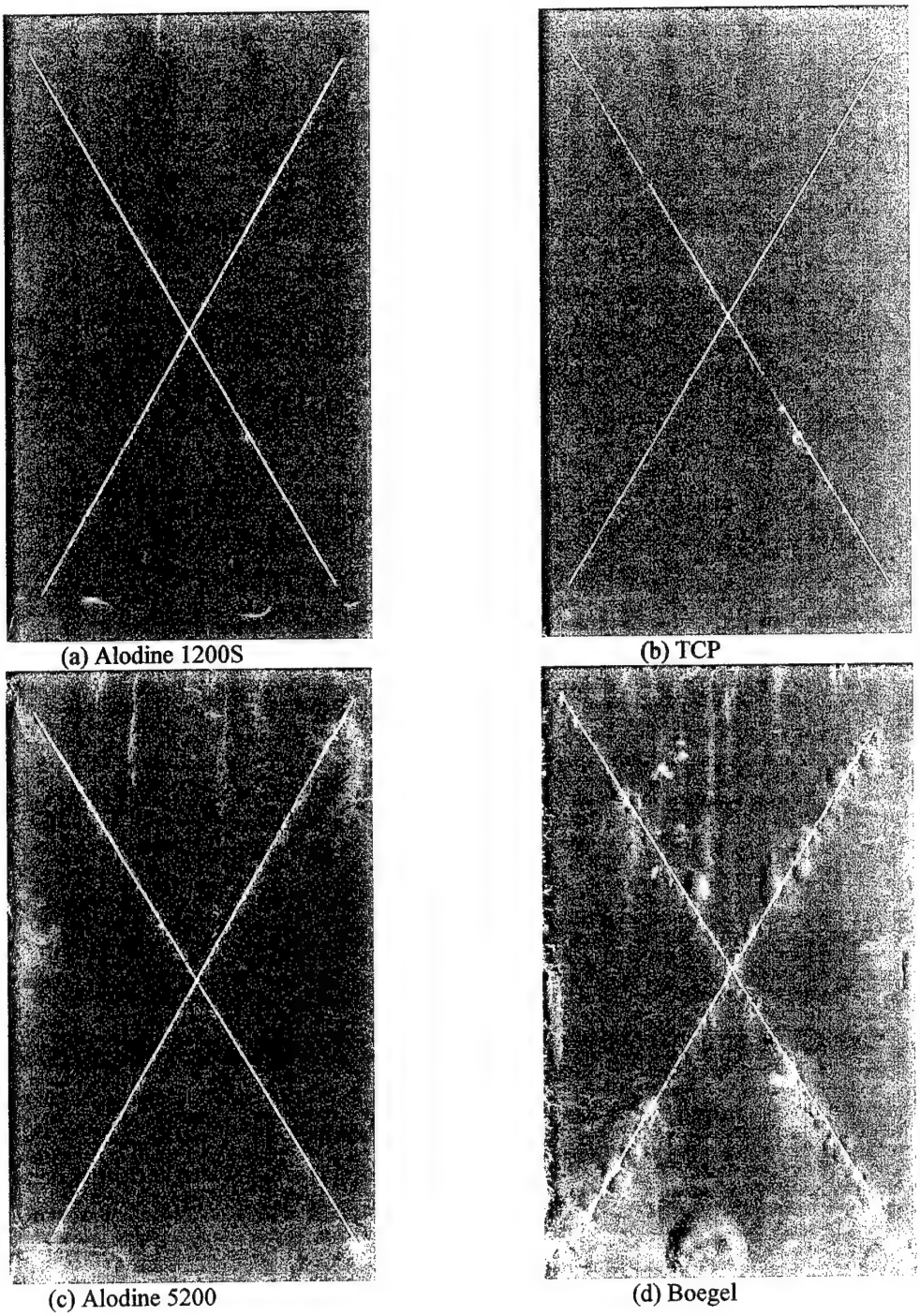


Figure 13. Al 7075 with 53022/53039 at 3000-hr ASTM B 117.

4. Discussion

The purpose of this study was to provide ASTM B 117 accelerated corrosion performance data for alternatives to Cr^{+6} -based Alodine 1200S. It should be stressed that good performance in accelerated corrosion testing alone does not guarantee a good conversion coating. Other conditions such as corrosion performance under thermal and humidity cycling, coating system adhesion, visible color changes to the substrate surface (for quality control) upon pretreatment application, toxicity issues other than Cr^{+6}, as well as the logistics and costs of process-application steps, all play significant roles in determination of a viable pretreatment alternative. In order to obtain the most information possible, this overall ESTCP/JG-PP effort included additional laboratory procedures such as GM 9540P, SO_2 salt fog, and adhesion methods, all conducted on the same alloy/pretreatment/coating combinations investigated in this portion of the study. Variations in application procedures such as surface preparations, bath conditions for dip processes, and spray applications were also included. These additional results may be accessed in other ESTCP reports. Information on these documents is available via ESTCP/JG-PP contacts <http://www.estcp.org/>. Ultimately, data from this study as well as data from all of the other evaluations will be offered to help end users identify potential alternatives to chromate conversion coatings currently in use by original equipment manufacturers (OEMs) and depots.

It is likely that more than one pretreatment may be a reasonable replacement for Alodine 1200S. As seen from data in this study as well as previous studies [1, 11], pretreatments that often work well on one aluminum alloy, may not always work well for another. However, this does not necessarily mean that a unique pretreatment is needed for every unique situation. For simplicity as well as economies of scale, the best possible benefit for replacing Alodine 1200S would be gained by minimizing the number of finalists to as few as possible. A pretreatment that has well-rounded performance across many aluminum alloys would be the most desirable. In this particular study, two pretreatments (Alodine 5200 and NAVAIR TCP) were the best all-around non-Cr^{+6} performers in ASTM B 117 salt fog exposure. Although NAVAIR TCP pretreatment is Cr^{+3} based, toxicity studies on trivalent chromium exposure indicate no carcinogenic or other hazards similar to those found in Cr^{+6} pretreatments such as Alodine 1200S [12, 13]. Nevertheless, environmental regulatory bodies such as those found in California and the European Union have implemented or indicated future stricter guidelines concerning the use of chromium-containing pretreatments.

A previous study [1] of cyclic corrosion resistance under GM 9540P indicated a slight performance advantage for TCP over Alodine 5200. However, if trivalent chromium-based pretreatments such as TCP are not acceptable or allowed for implementation due to their total chromium content, Alodine 5200 should perform quite satisfactorily. Additional laboratory and

automotive proving ground [14] studies involving Alodine 5200 have also shown good performance on a variety of Al alloys using 53022/53039-based CARC systems [11, 15–17].

Many currently fielded weapon systems in use by the services continue to use hexavalent chromate-containing coating systems such as 23377/85285 and 85582c1/85285. This additional Cr^{+6} enables many prospective Cr^{+6} free pretreatments to "coast" though with their actual overall contribution to the total system obscured. Thus, in order to truly determine the degree of enhanced corrosion resistance gained from a hexavalent chromium-free pretreatment, a hexavalent chromium-free organic coating system must also be used when performing corrosiontest procedures. Current and future acquisition systems such as the Advanced Amphibious Assault Vehicle and the Brigade Combat Team Stryker are already mandating Cr^{+6} free organic coating systems. This trend is likely to continue and potentially may even be applied to some fielded DOD vehicles and weapons systems during overhauls. In order to clearly delineate the best possible Cr^{+6} free pretreatment(s), additional experimental results from a wide range of methods, in addition to field tests on actual systems from NAVAIR and other participating DOD activities will be critical.

5. Conclusions

- Pretreatment performance varies among varying alloys.
- DOD coating systems formulated with Cr^{+6} additives provided significantly enhanced corrosion resistance versus coatings without Cr^{+6}.
- Alodine 5200 and NAVAIR TCP Cr^{+3} performed best overall in ASTM B 117 salt fog among non-Cr^{+6} based pretreatments with performance at or near Cr^{+6} based Alodine 1200S across all alloys and coating systems examined.
- Commercially available Alodine 5200, in conjunction with the chromium-free organic coatings tested in this study, provides a completely chrome-free coating system with good corrosion resistance.

6. References

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Appendix. Complete 3000-hr ASTM B 117 Neutral Salt Fog ASTM D 1654 Creepback Ratings

Table A-1. Al 2024–T3 panel designation, coating system, and ratings.

Pretreatment	23377/85285					85582c1/85285					85582nc/85285				
Alodine 1200S	2-01	2-02	2-03	2-04	2-05	2-06	2-07	2-08	2-09	2-10	2-11	2-12	2-13	2-14	2-15
Rating		6			7						7	6	6		
TCP10 (NAVAIR)	2-101	2-102	2-103	2-104	2-105	2-106	2-107	2-108	2-109	2-110	2-111	2-112	2-113	2-114	2-115
Rating															
Alodine 5200	2-201	2-202	2-203	2-204	2-205	2-206	2-207	2-208	2-209	2-210	2-211	2-212	2-213	2-214	2-215
Rating											5	7	7	7	6
Sanchem 7000	2-301	2-302	2-303	2-304	2-305	2-306	2-307	2-308	2-309	2-310	2-311	2-312	2-313	2-314	2-315
Rating						8	7			6					
X-IT PreKote	2-401	2-402	2-403	2-404	2-405	2-406	2-407	2-408	2-409	2-410	2-411	2-412	2-413	2-414	2-415
Rating			8	8											
Oxsilan AI-0500	2-501	2-502	2-503	2-504	2-505	2-506	2-507	2-508	2-509	2-510	2-511	2-512	2-513	2-514	2-515
Rating											7	5	7	7	7
Chemidize 727ND	2-601	2-602	2-603	2-604	2-605	2-606	2-607	2-608	2-609	2-610	2-611	2-612	2-613	2-614	2-615
Rating		6			6				7						
BI-K Aklimate	2-701	2-702	2-703	2-704	2-705	2-706	2-707	2-708	2-709	2-710	2-711	2-712	2-713	2-714	2-715
Rating				7	6	8	8	8	8	8					
Boegel	2-801A	2-802A	2-803A	2-804A	2-805A	2-806A	2-807A	2-808A	2-809A	2-810A	2-811A	2-812A	2-813A	2-814A	2-815A
Rating												7	7	7	7

Notes: Solid colors depict normal scribe creepback from corrosion.
Vertical crosshatching denotes adhesion failure.
Diagonal blistering away from immediate scribe regions.

Table A-2. Al 2024–T3 panel designation, coating system, and ratings.

Pretreatment	53030/53039					53022/53039				
Alodine 1200S	2-16	2-17	2-18	2-19	2-20	2-21	2-22	2-23	2-24	2-25
Rating	7	7			7					
TCP10 (NAVAIR)	2-116	2-117	2-118	2-119	2-120	2-121	2-122	2-123	2-124	2-125
Rating										
Alodine 5200	2-216	2-217	2-218	2-219	2-220	2-221	2-222	2-223	2-224	2-225
Rating	7						7	6	7	7
Sanchem 7000	2-316	2-317	2-318	2-319	2-320	2-321	2-322	2-323	2-324	2-325
Rating										
X-IT PreKote	2-416	2-417	2-418	2-419	2-420	2-421	2-422	2-423	2-424	2-425
Rating										
Oxsilan AI-0500	2-516	2-517	2-518	2-519	2-520	2-521	2-522	2-523	2-524	2-525
Rating										
Chemidize 727ND	2-616	2-617	2-618	2-619	2-620	2-621	2-622	2-623	2-624	2-625
Rating										
BI-K Aklimate	2-716	2-717	2-718	2-719	2-720	2-721	2-722	2-723	2-724	2-725
Rating										
Boegel	2-816A	2-817A	2-818A	2-819A	2-820A	2-821A	2-822A	2-823A	2-824A	2-825A
Rating							7		7	6

Notes: Solid colors depict normal scribe creepback from corrosion.

Table A-3. Al 2219–T87 panel designation, coating system, and ratings.

Pretreatment	23377/85285					85582c1/85285					85582nc/85285				
Alodine 1200S	9-01	9-02	9-03	9-04	9-05	9-06	9-07	9-08	9-09	9-10	9-11	9-12	9-13	9-14	9-15
Rating											7	7	7	6	6
TCP 10 (NAVAIR)	9-101	9-102	9-103	9-104	9-105	9-106	9-107	9-108	9-109	9-110	9-111	9-112	9-113	9-114	9-115
Rating	4				6						2	4	2	3	6
Alodine 5200	9-201	9-202	9-203	9-204	9-205	9-206	9-207	9-208	9-209	9-210	9-211	9-212	9-213	9-214	9-215
Rating											6	6	6	6	6
Sanchem 7000	9-301	9-302	9-303	9-304	9-305	9-306	9-307	9-308	9-309	9-310	9-311	9-312	9-313	9-314	9-315
Rating		2	4			5	7	6	7	6					
X-IT PreKote	9-401	9-402	9-403	9-404	9-405	9-406	9-407	9-408	9-409	9-410	9-411	9-412	9-413	9-414	9-415
Rating	7	7	7	8	7	8	8	8	9	8					
Oxsilan AI-0500	9-501	9-502	9-503	9-504	9-505	9-506	9-507	9-508	9-509	9-510	9-511	9-512	9-513	9-514	9-515
Rating	7					3	3	2		2	5	7	5	5	6
Chemidize 727ND	9-601	9-602	9-603	9-604	9-605	9-606	9-607	9-608	9-609	9-610	9-611	9-612	9-613	9-614	9-615
Rating	4		4	6	7	7					4		1		4
BI-K Aklimate	9-701	9-702	9-703	9-704	9-705	9-706	9-707	9-708	9-709	9-710	9-711	9-712	9-713	9-714	9-715
Rating	6					6	7	7	7	6					
Boegel	9-801A	9-802A	9-803A	9-804A	9-805A	9-806A	9-807A	9-808A	9-809A	9-810A	9-811A	9-812A	9-813A	9-814A	9-815A
Rating		5	4	4	5	6	6	5	5	6	4	4	4	4	

Notes: Solid colors depict normal scribe creepback from corrosion.
Vertical crosshatching denotes adhesion failure.
Diagonal blistering away from immediate scribe regions.
Fine textured crosshatching denotes adhesion failure AND blistering away from scribe.

Table A-4. Al 2219–T87 panel designation, coating system, and ratings.

Pretreatment	53030/53039					53022/53039				
Alodine 1200S	9-16	9-17	9-18	9-19	9-20	9-21	9-22	9-23	9-24	9-25
Rating	6	5	7	7	5					
TCP10 (NAVAIR)	9-116	9-117	9-118	9-119	9-120	9-121	9-122	9-123	9-124	9-125
Rating	5	5	4	5	6	5	5	5		5
Alodine 5200	9-216	9-217	9-218	9-219	9-220	9-221	9-222	9-223	9-224	9-225
Rating	5	4	5	4	5			4		4
Sanchem 7000	9-316	9-317	9-318	9-319	9-320	9-321	9-322	9-323	9-324	9-325
Rating										
X-IT PreKote	9-416	9-417	9-418	9-419	9-420	9-421	9-422	9-423	9-424	9-425
Rating										
Oxsilan AI-0500	9-516	9-517	9-518	9-519	9-520	9-521	9-522	9-523	9-524	9-525
Rating										
Chemidize 727ND	9-616	9-617	9-618	9-619	9-620	9-621	9-622	9-623	9-624	9-625
Rating						7	7	7	7	
BI-K Aklimate	9-716	9-717	9-718	9-719	9-720	9-721	9-722	9-723	9-724	9-725
Rating										
Boegel	9-816A	9-817A	9-818A	9-819A	9-820A	9-821A	9-822A	9-823A	9-824A	9-825A
Rating										

Notes: Solid colors depict normal scribe creepback from corrosion.
Diagonal crosshatching denotes blistering away from immediate scribe regions.

Table A-5. Al 5083–H131 panel designation, coating system, and ratings.

Pretreatment	23377/85285					85582c1/85285					85582nc/85285				
Alodine 1200S	5-01	5-02	5-03	5-04	5-05	5-06	5-07	5-08	5-09	5-10	5-11	5-12	5-13	5-14	5-15
Rating															
TCP10 (NAVAIR)	5-101	5-102	5-103	5-104	5-105	5-106	5-107	5-108	5-109	5-110	5-111	5-112	5-113	5-114	5-115
Rating															
Alodine 5200	5-201	5-202	5-203	5-204	5-205	5-206	5-207	5-208	5-209	5-210	5-211	5-212	5-213	5-214	5-215
Rating															
Sanchem 7000	5-301	5-302	5-303	5-304	5-305	5-306	5-307	5-308	5-309	5-310	5-311	5-312	5-313	5-314	5-315
Rating	8					8				9					
X-IT PreKote	5-401	5-402	5-403	5-404	5-405	5-406	5-407	5-408	5-409	5-410	5-411	5-412	5-413	5-414	5-415
Rating						8	8	9	9	6					
Oxsilan AL-0500	5-501	5-502	5-503	5-504	5-505	5-506	5-507	5-508	5-509	5-510	5-511	5-512	5-513	5-514	5-515
Rating						7	9	9		9	7				
Chemidize 727ND	5-601	5-602	5-603	5-604	5-605	5-606	5-607	5-608	5-609	5-610	5-611	5-612	5-613	5-614	5-615
Rating						9	8	6	9	9					
BI-K Aklimate	5-701	5-702	5-703	5-704	5-705	5-706	5-707	5-708	5-709	5-710	5-711	5-712	5-713	5-714	5-715
Rating						9	9	9	9	9					
Boegel	5-801A	5-802A	5-803A	5-804A	5-805A	5-806A	5-807A	5-808A	5-809A	5-810A	5-811A	5-812A	5-813A	5-814A	5-815A
Rating											8		7		

Notes: Solid colors depict normal scribe creepback from corrosion.
Vertical crosshatching denotes adhesion failure.
Diagonal crosshatching denotes blistering away from immediate scribe regions.

Table A-6. Al 5083–H131 panel designation, coating system, and ratings.

Pretreatment	53030/53039					53022/53039				
Alodine 1200S	5-16	5-17	5-18	5-19	5-20	5-21	5-22	5-23	5-24	5-25
Rating					6					
TCP10 (NAVAIR)	5-116	5-117	5-118	5-119	5-120	5-121	5-122	5-123	5-124	5-125
Rating	6			6			7	6	6	6
Alodine 5200	5-216	5-217	5-218	5-219	5-220	5-221	5-222	5-223	5-224	5-225
Rating	6			7						
Sanchem 7000	5-316	5-317	5-318	5-319	5-320	5-321	5-322	5-323	5-324	5-325
Rating										
X-IT PreKote	5-416	5-417	5-418	5-419	5-420	5-421	5-422	5-423	5-424	5-425
Rating										
Oxsilan AI-0500	5-516	5-517	5-518	5-519	5-520	5-521	5-522	5-523	5-524	5-525
Rating										
Chemidize 727ND	5-616	5-617	5-618	5-619	5-620	5-621	5-622	5-623	5-624	5-625
Rating										
BI-K Aklimate	5-716	5-717	5-718	5-719	5-720	5-721	5-722	5-723	5-724	5-725
Rating										
Boegel	5-816A	5-817A	5-818A	5-819A	5-820A	5-821A	5-822A	5-823A	5-824A	5-825A
Rating										

Notes: Solid colors depict normal scribe creepback from corrosion.

Table A-7. Al 7075–T6 panel designation, coating system, and ratings.

Pretreatment	23377/85285					85582c1/85285					85582nc/85285				
Alodine 1200S	7-01	7-02	7-03	7-04	7-05	7-06	7-07	7-08	7-09	7-10	7-11	7-12	7-13	7-14	7-15
Rating															
TCP10 (NAVAIR)	7-101	7-102	7-103	7-104	7-105	7-106	7-107	7-108	7-109	7-110	7-111	7-112	7-113	7-114	7-115
Rating	8	8	8	8	8	8							6		
Alodine 5200	7-201	7-202	7-203	7-204	7-205	7-206	7-207	7-208	7-209	7-210	7-211	7-212	7-213	7-214	7-215
Rating															
Sanchem 7000	7-301	7-302	7-303	7-304	7-305	7-306	7-307	7-308	7-309	7-310	7-311	7-312	7-313	7-314	7-315
Rating							4		2				6		
X-IT PreKote	7-401	7-402	7-403	7-404	7-405	7-406	7-407	7-408	7-409	7-410	7-411	7-412	7-413	7-414	7-415
Rating									7		7				
Oxsilan AI-0500	7-501	7-502	7-503	7-504	7-505	7-506	7-507	7-508	7-509	7-510	7-511	7-512	7-513	7-514	7-515
Rating															
Chemidze 727ND	7-601	7-602	7-603	7-604	7-605	7-606	7-607	7-608	7-609	7-610	7-611	7-612	7-613	7-614	7-615
Rating						5	4								
BI-K Aklimate	7-701	7-702	7-703	7-704	7-705	7-706	7-707	7-708	7-709	7-710	7-711	7-712	7-713	7-714	7-715
Rating						7	4	5	8	5					
Boegel	7-801A	7-802A	7-803A	7-804A	7-805A	7-806A	7-807A	7-808A	7-809A	7-810A	7-811A	7-812A	7-813A	7-814A	7-815A
Rating															

Notes: Solid colors depict normal scribe creepback from corrosion.
Vertical crosshatching denotes adhesion failure.
Fine textured crosshatching denotes adhesion failure AND blistering away from scribe.

Table A-8. Al 7075–T6 panel designation, coating system, and ratings.

Pretreatment	53030/53039					53022/53039				
Alodine 1200S	7-16	7-17	7-18	7-19	7-20	7-21	7-22	7-23	7-24	7-25
Rating	7				7	7	5		6	6
TCP10 (NAVAIR)	7-116	7-117	7-118	7-119	7-120	7-121	7-122	7-123	7-124	7-125
Rating	7	7	5	7	6					
Alodine 5200	7-216	7-217	7-218	7-219	7-220	7-221	7-222	7-223	7-224	7-225
Rating	6	5	7	7	6		6	6	5	7
Sanchem 7000	7-316	7-317	7-318	7-319	7-320	7-321	7-322	7-323	7-324	7-325
Rating							6	6	5	4
X-IT PreKote	7-416	7-417	7-418	7-419	7-420	7-421	7-422	7-423	7-424	7-425
Rating										
Oxsilan AI-0500	7-516	7-517	7-518	7-519	7-520	7-521	7-522	7-523	7-524	7-525
Rating			No Panel						7	
Chemidze 727ND	7-616	7-617	7-618	7-619	7-620	7-621	7-622	7-623	7-624	7-625
Rating										
BI-K Aklimate	7-716	7-717	7-718	7-719	7-720	7-721	7-722	7-723	7-724	7-725
Rating										
Boegel	7-816A	7-817A	7-818A	7-819A	7-820A	7-821A	7-822A	7-823A	7-824A	7-825A
Rating						4	4	5	5	5

Notes: Solid colors depict normal scribe creepback from corrosion.

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14. ABSTRACT
This study examines corrosion resistance of eight nonchromate conversion coatings vs. hexavalent chromium based Alodine 1200S controls on scribed coated test panels of aluminum alloys 2024, 2219, 5083, and 7075. Five representative Department of Defense primer/topcoat organic coating systems were evaluated for each of the conversion coating/alloy combinations. Scribed panels were exposed using ASTM B 117 (neutral salt fog) for 3000 hr and were photographed and measured at 1, 2, and 3 weeks. Subsequent measurements were taken every 500 hr until "3000 hr" was reached or until failures from scribe creepback and/or via blistering occurred using method ASTM D 1654. Differences in pretreatment performance based upon variation in coating type as well as alloy were noted. Relationships between data from this study and data collected from previous cyclic acceleration corrosion exposure and how they may relate with respect to implementation of nonchromate pretreatments for various military applications are discussed.

15. SUBJECT TERMS
corrosion, saltfog, ASTM B 117, GM 9540P, cyclic accelerated corrosion, aluminum, hexavalent chromium, nonchromate, chromate, conversion coating

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